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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA GENERAL WORKING PAPER NO. 10 075

OPERATIONAL ASPECTS OF SIMULATING WEIGHTLESSNESS BY USE OF THE WATER IMMERSION TECHNIQUE

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
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OPERATIONAL ASPECTS OF SIMULATING WEIGHTLESSNESS BY USE OF THE WATER IMMERSION TECHNIQUE

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CONTENTS

Section | Page

FIGURES

ABBREVIATIONS

A	area
B_F	buoyant force
c.b.	center of buoyancy
c.g.	center of gravity
EVA	extravehicular activity
h	elevation
IVA	intravehicular activity
P	pressure
TDA	target docking adapter
W	weight
X,Y,Z,ϕ,θ,ψ	reference directions for six degrees of freedom of motion
γ	specific weight

1.0 OBJECTIVE OF REPORT

This report is intended to provide an introductory source of information on the operational aspects of simulating weightlessness by use of the water immersion technique. This information is based on experience with the technique in simulation of extravehicular activity (EVA) during the Gemini Program. The report will emphasize those areas of the Gemini experience associated with the simulation of the total EVA.

2.0 INTRODUCTION

The Gemini EVA experience established the significance of the water immersion technique in the evaluation of EVA flight plans and in the training of flight crews. The limitations of the zero-gravity aircraft simulations and the ground training at earth gravity were emphasized by the Gemini IX-A and XI results, when unexpected problems caused premature termination of the planned EVA. The use of the water immersion technique for both the development of procedures and crew training contributed significantly to the success of the Gemini XII EVA.

The water immersion technique simulates weightlessness by providing the immersed subject six degrees of freedom of motion. This freedom of motion is identical to that experienced in space (fig. 2-1). The main advantage of the water immersion technique over other methods of simulating weightlessness is that it permits continuous performance of the total task, while not limiting the subject's operating environment by the use of cables or suspension rigs. The technique was found to be particularly applicable to the problems of EVA body restraint and positioning. The validity of the technique in solving these problems as well as assessing workloads was confirmed by Gemini in-flight results and postflight evaluation. Recognition of the value of the technique in simulation of the total EVA experience during the Gemini Program has brought the technique to its present status, which is one of prime importance in the training of Apollo crews for EVA and the evaluation of EVA flight plans.

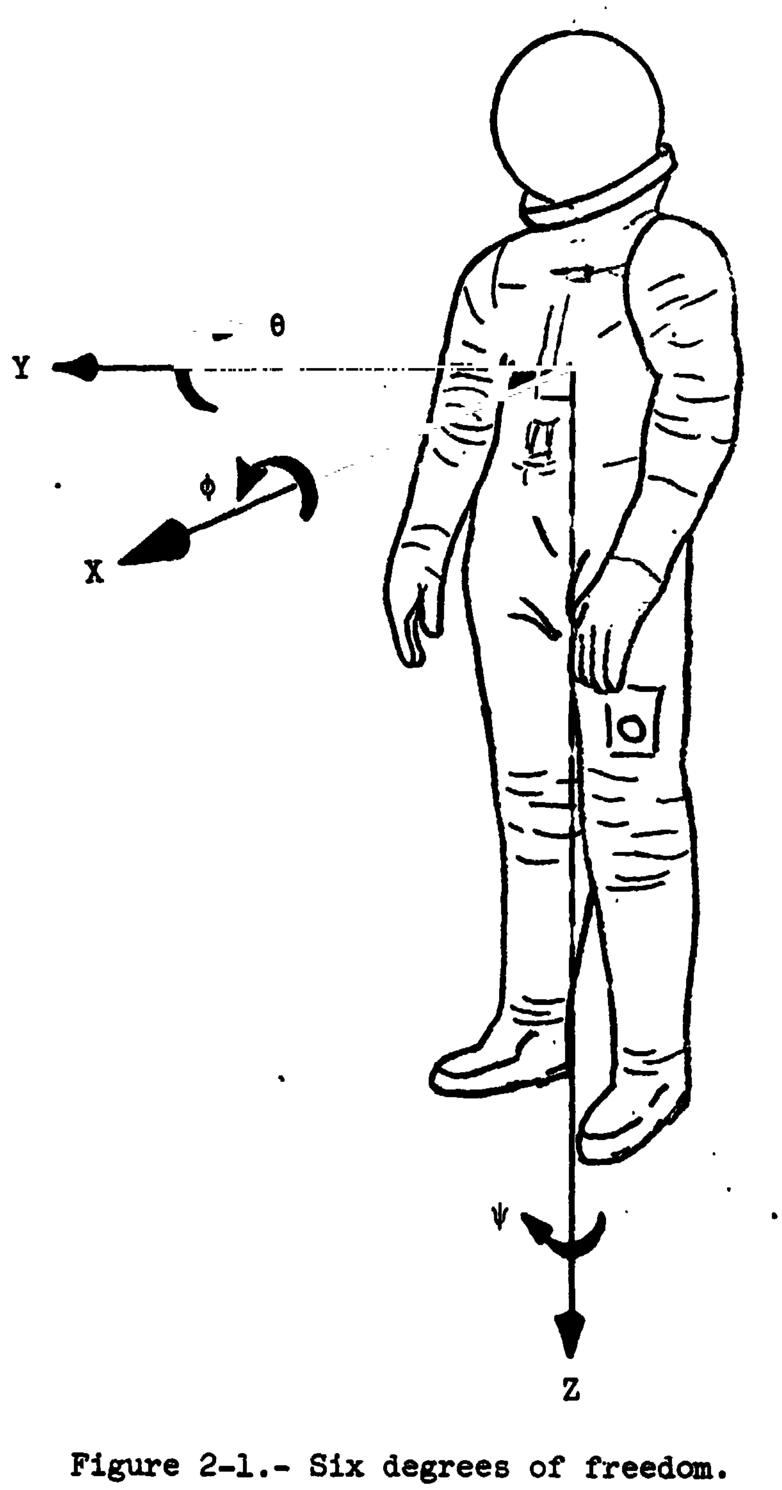


Figure 2-1.- Six degrees of freedom.

3.0 REVIEW OF BASIC PRINCIPLES

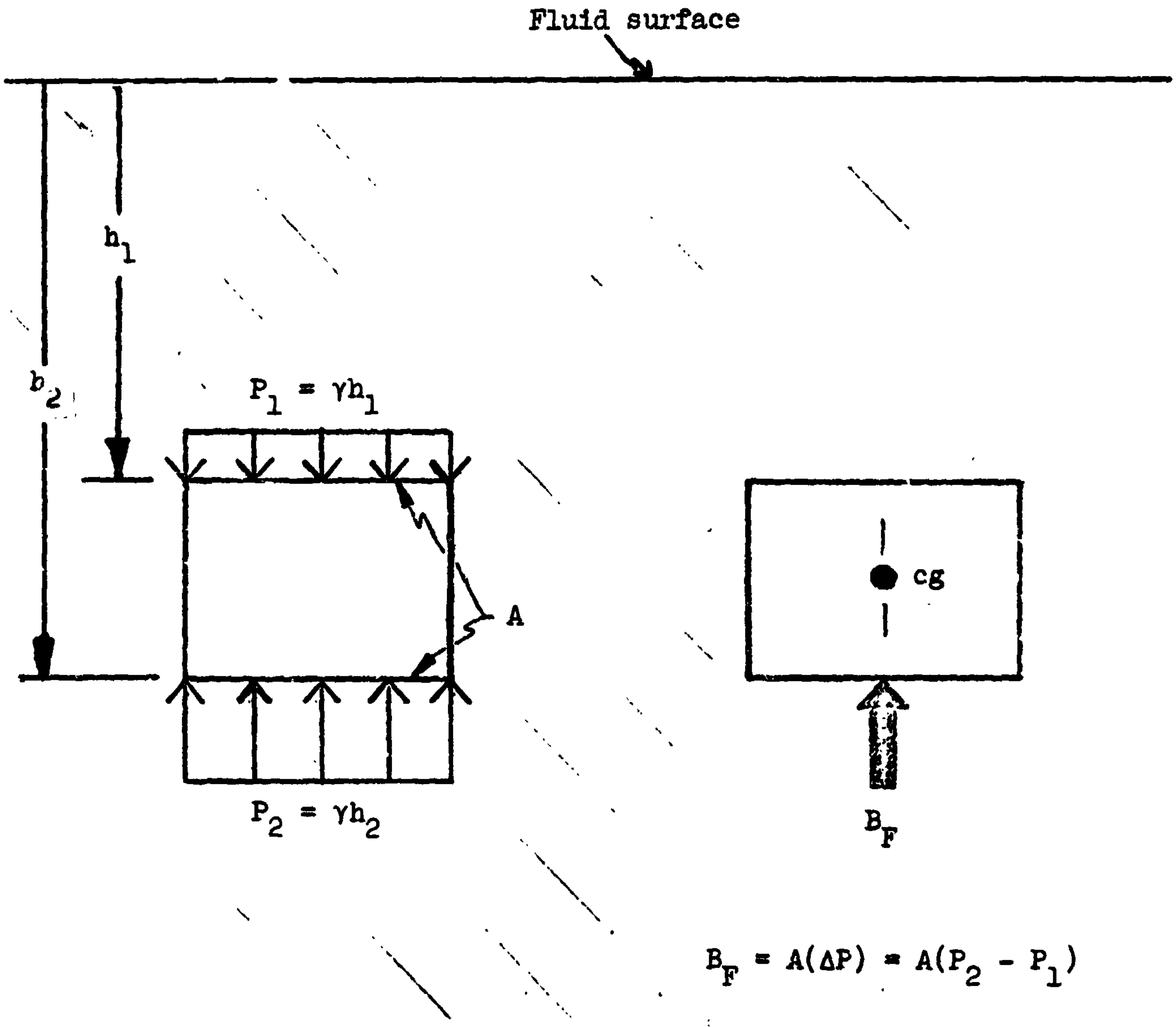
The water immersion technique provides the immersed subject with six degrees of freedom of motion by rendering him neutrally stable in translation and rotation. A review of the basic physical principles involved is provided to facilitate a better appreciation of the simulation and some of the problems encountered, which are discussed later in this report.

3.1 NEUTRAL STABILITY IN VERTICAL PLANES

A body placed in a fluid experiences an upward force equal to the weight of the volume of fluid displaced by the body. This force results from the pressure differential across the body (fig. 3-1(a)). The force, known as the buoyant force, acts upward through the center of gravity of the displaced fluid, which is also the center of buoyancy of the body (fig. 3-1(b)). The body floats in the fluid when the buoyant force is equal to the weight of the body. The body floating partially immersed in a static fluid is vertically stable (fig. 3-2). Its average density is less than that of the fluid. A vertical displacement, upward or downward, results in an unbalanced force tending to return the body to its original position. However, vertical stability is not the complete condition desired in the simulation of weightlessness. The average density, and hence the weight of the body must be increased so that the entire body is immersed (fig. 3-3). The average density of the body is made equal to the density of the fluid. The buoyant force has obtained its maximum value since no additional fluid can be displaced by the body. With the weight of the body equal to the maximum buoyant force, the body can be displaced without an unbalanced force resulting. The body is then neutrally stable in the vertical planes. In the water immersion technique of simulating weightlessness, the subject is made neutrally stable in the vertical planes. This condition is also called neutral buoyancy.

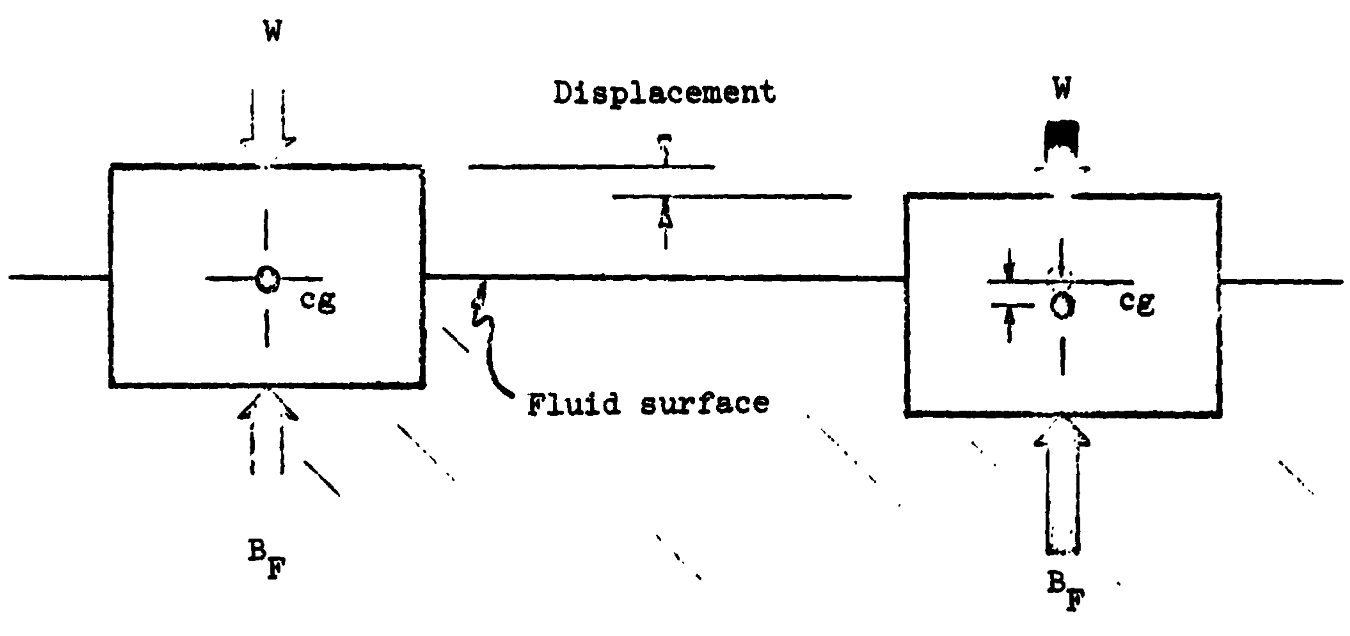
3.2 NEUTRAL STABILITY IN HORIZONTAL PLANES

Neutral stability of immersed bodies in horizontal planes is not problematical. The body can be displaced horizontally without an unbalanced force resulting. Thus, a body can be shown to possess neutral stability in translation when it is rendered neutrally stable in the vertical planes or neutrally buoyant.



(a) Body in fluid. (b) Displaced fluid.

Figure 3-1.- Buoyant force.



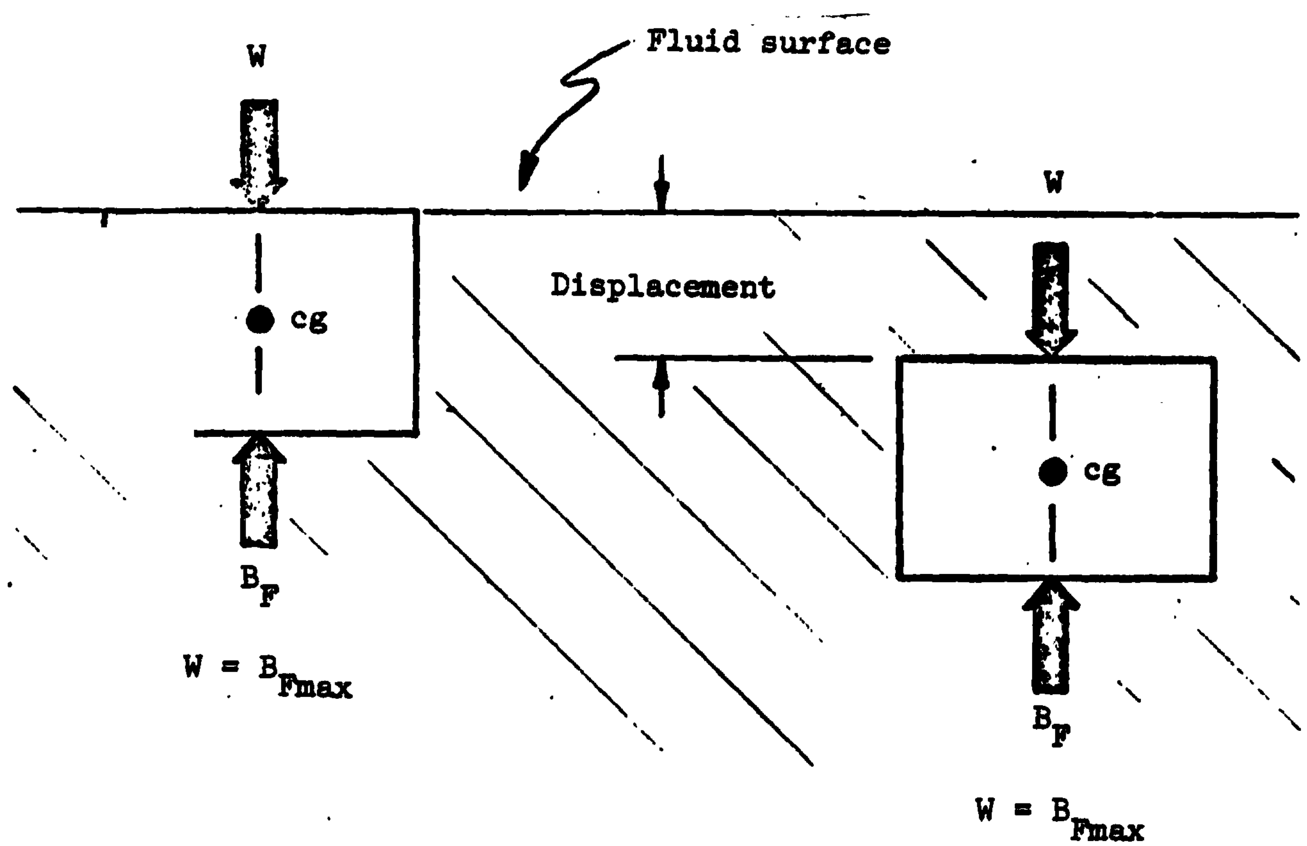
$W = B_F$

(a) Body at rest, forces balanced.

$B_F > W$

(b) Body displaced, forces unbalanced.

Figure 3-2.- Vertical stability.



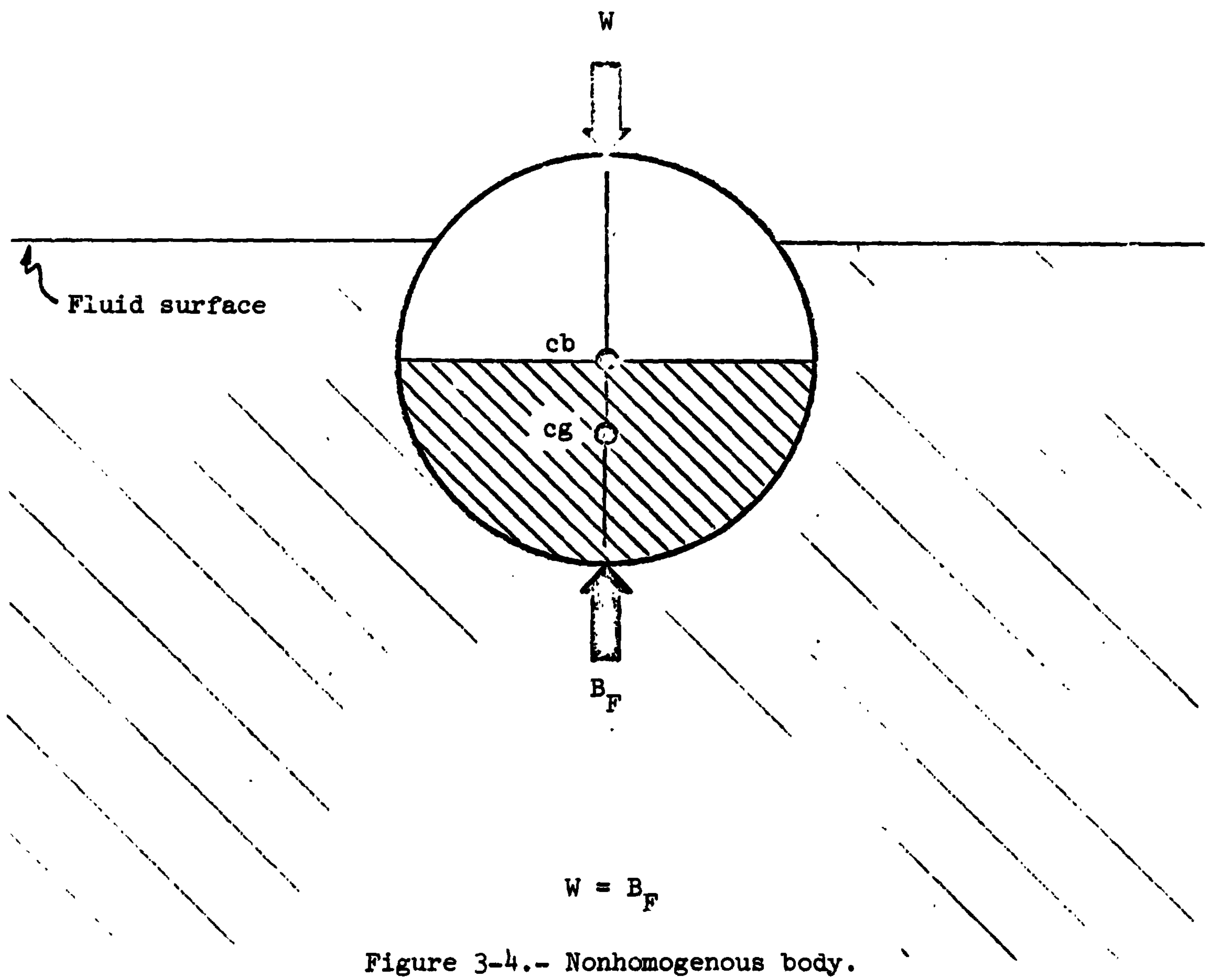
(a) Body at rest, forces balanced.

(b) Body displaced, forces remain balanced.

Figure 3-3.- Neutral vertical stability.

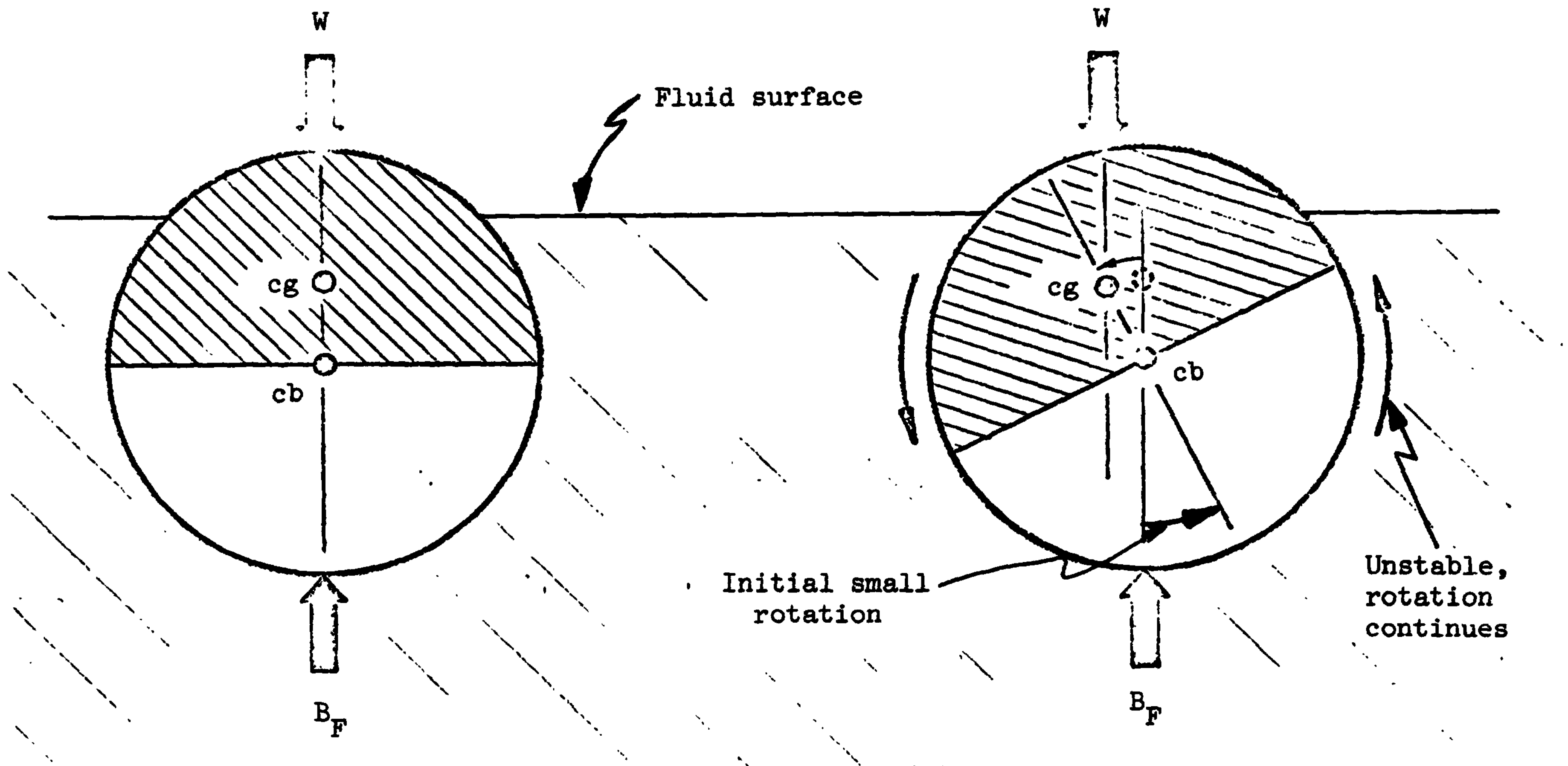
3.3 NEUTRAL STABILITY IN ROTATION

Consider the floating body in figure 3-4. The density of the shaded area of the body is greater than the light area. The body will float in either unstable, stable, or neutral equilibrium. The body floats in unstable equilibrium when a small rotation sets up a couple which tends to increase its rotation (fig. 3-5). A couple results because of the displacement of the center of gravity and the center of buoyancy of the body from a vertical line along which the buoyant force and weight of the body were acting in direct opposition. A body floats in stable equilibrium when a small rotation sets up a couple which tends to return the body to its original position (fig. 3-6). As was the case with translation, the desired condition in rotation in the simulation of weightlessness is one of neutral stability. The immersed or floating body in a condition of neutral equilibrium possesses neutral stability in rotation. This condition is illustrated in figure 3-7. If the body is homogenous (constant density throughout), a rotation of the body does not result in a couple. A couple does not result because the center of gravity of the body continues to coincide with the center of buoyancy of the body as the body is rotated. Therefore, in application of the technique, attempts will be made to have the center of gravity and the center of buoyancy of objects coincide.



$W = B_F$

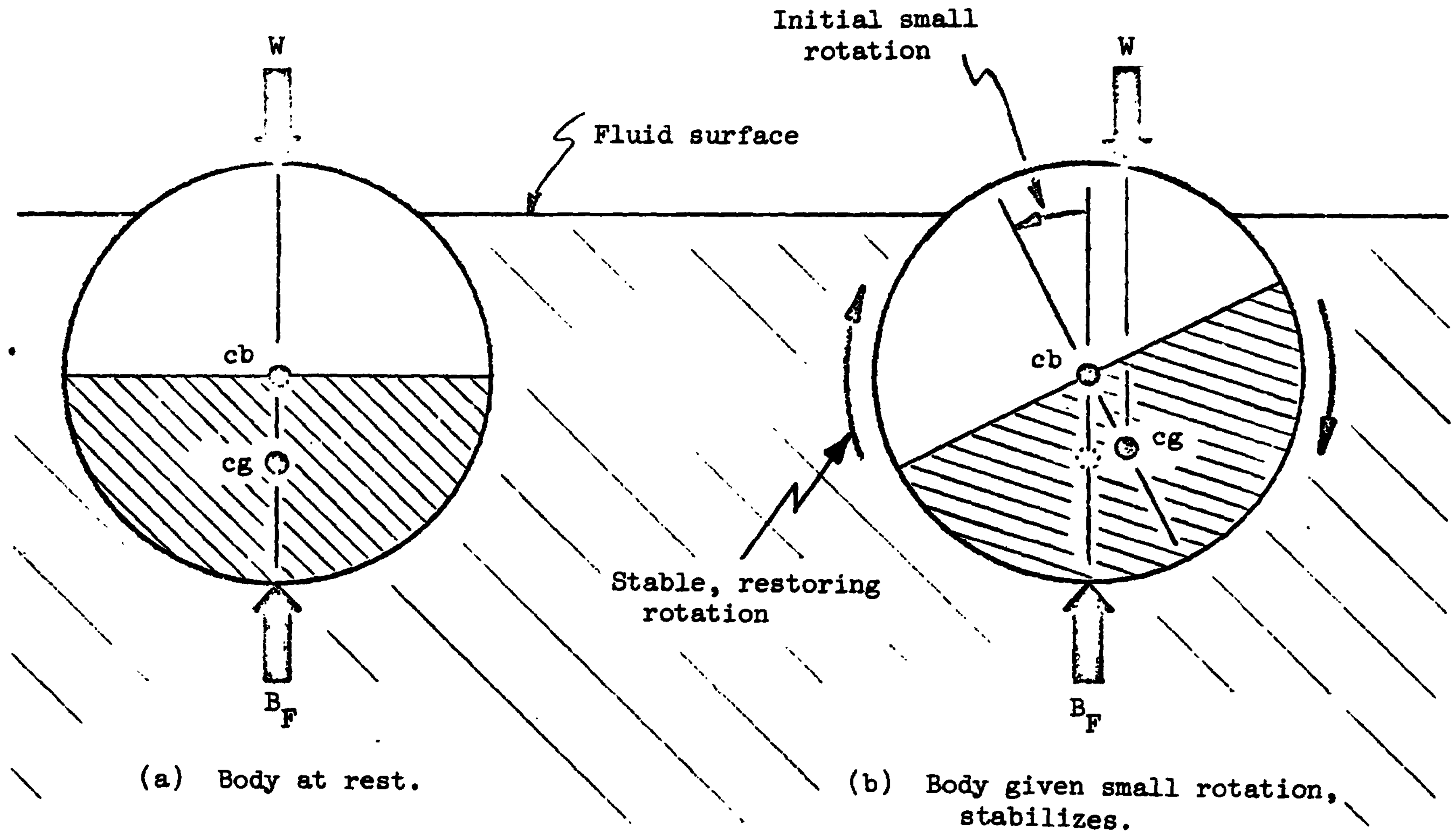
Figure 3-4.- Nonhomogenous body.



(a) Body at rest.

(b) Body given small rotation, becomes unstable.

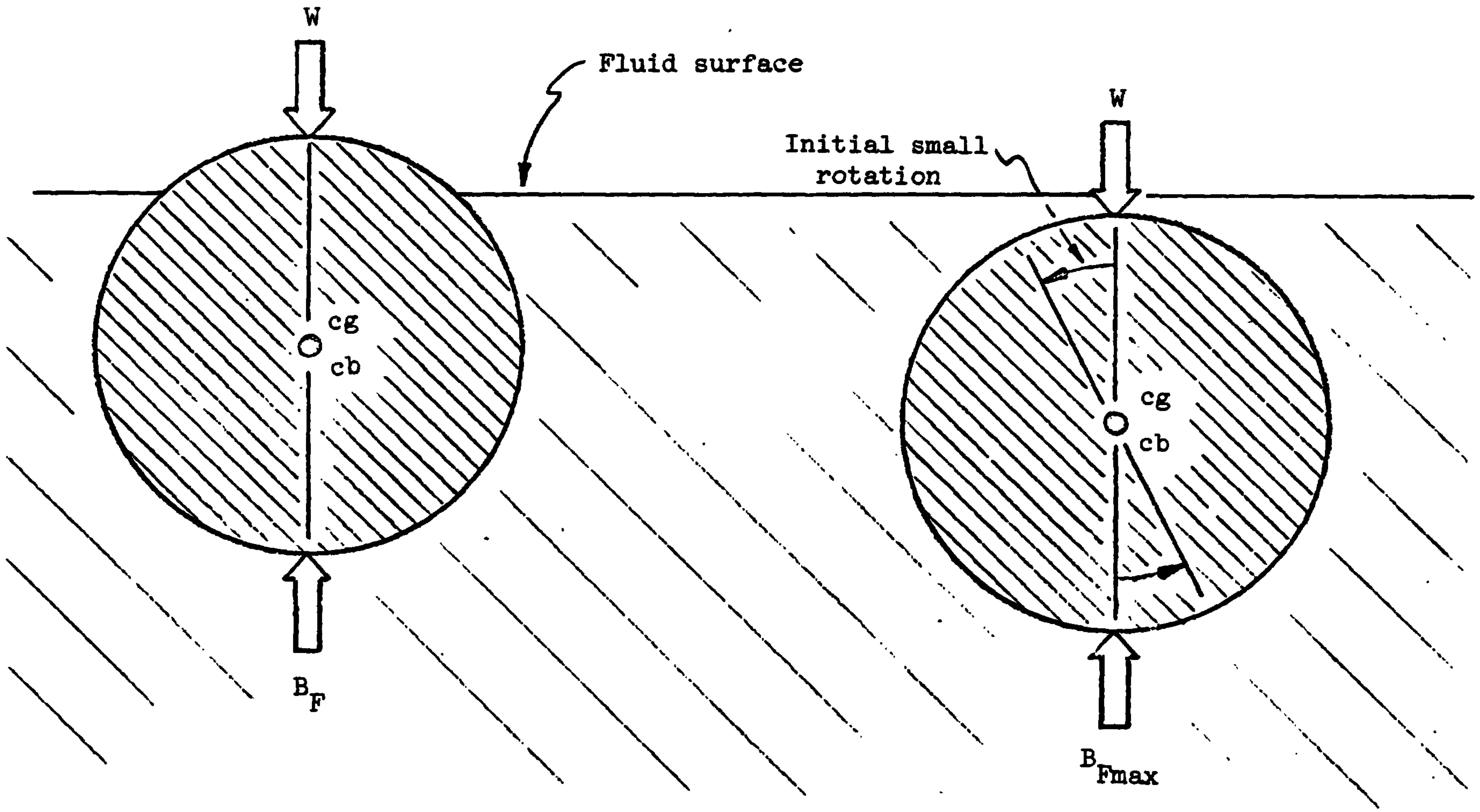
Figure 3-5.- Unstable equilibrium.



(a) Body at rest.

(b) Body given small rotation, stabilizes.

Figure 3-6.- Stable equilibrium.



(a) Body at rest.

(b) Body given small rotations, maintains equilibrium.

Figure 3-7.- Neutral equilibrium or neutral stability in rotation.

4.0 LIMITATIONS OF SIMULATION

The water immersion technique in simulating weightlessness must render the subject neutrally stable in translation and rotation. In other words, the subject must be neutrally buoyant and float in neutral equilibrium. The principles by which the water immersion technique can accomplish these objectives were illustrated in section 3.0. However, there are certain inherent problems in the body represented by the man-suit system and the water immersion technique which tend to complicate the simulation of weightlessness. Some of these problems tend to limit the simulation. Consideration of these problems in the application of the water immersion technique is necessary to attain a high-fidelity simulation. The intent of this section of the report is to discuss these problems in detail in order to relate their total effect upon the simulation and methods of minimizing this effect.

4.1 VERTICAL STABILITY

In the water immersion technique of simulating weightlessness, the subject is made neutrally buoyant. The subject is neutrally buoyant when his density is equal to the density of water. For a subject in a pressurized suit, up to 150 pounds of ballast weights (usually lead) must be added to attain neutral buoyancy. These weights are located about the subject's arms, legs, and torso, in such a manner as to minimize interference with his performance of activity. Experience with the technique has indicated that neutral buoyancy may be lost during a simulation. Several causes of the loss of neutral buoyancy have been noted and are discussed briefly below.

4.1.1 Absorption of Water

Absorption of water by the pressure suit will increase the subject's weight, resulting in an unbalanced force tending to displace the subject downward. Once this unbalanced force is detected, which may be difficult if the subject is restrained during his activity, the subject can be rebalanced. Absorption of water by the suit was noted during the Gemini simulations. The rate of water absorption was such that the unbalanced force being generated was not detected until the subject had been immersed for 30 to 60 minutes. Water absorption was noted to be most severe with pressure suits that were being immersed for the first time and, particularly, pressure suits with extra layers of insulation such as used on the Gemini extravehicular suits. The effect of water absorption on the simulation was minimized by immersing new suits for several hours prior to their use in an underwater exercise.

4.1.2 Suit Volume Changes

Experience with the pressure suits used during the Gemini Program indicated that small increases in the suit volume could result during immersion. This increased suit volume apparently resulted from a stretching of the internal pressure bladder of the suit. The increase in suit volume caused an increase in the buoyant force, resulting in an unbalanced force tending to displace the subject upward. As was the case with the downward force resulting from absorption of water, once this upward force obtains sufficient magnitude to be noticeable, the subject can be rebalanced. The stretching characteristic of the internal pressure bladder was not common to all suits. The volume of some suits remained practically constant.

4.1.3 Air Mass Changes

During most simulations involving the use of a pressure suit, it is desired to maintain a constant suit-to-water pressure differential. This differential pressure is desired in order to minimize unique suit operating characteristics at various depths and to duplicate the suit dynamics experienced in the weightless environment of space. The magnitude of this differential normally approximates the suit to ambient pressure differential planned for the space activity being simulated. Maintaining this constant pressure differential means that the weight of the man-suit system will increase with depth due to the increased air mass required. This variation in air mass suggests a rebalance at various depths would be required. However, unless underwater activity is planned over a very large variation in depth, experience indicates the magnitude of the unbalanced force resulting from this variation in weight is too small to be noticeable during most activity simulated. As an example, the maximum magnitude of the unbalance force for a typical Apollo suit for a depth variation of 16 feet from the depth of balancing is less than 1/10 of a pound, which will be unnoticeable. If the subject were required to maintain a fixed, unrestrained position at depths greater than 16 feet from the depth he was balanced, movement would be noticeable in a few seconds. However, when the magnitude of this unbalanced force becomes detectable, the subject can be rebalanced.

4.1.4 Foam Compressibility

When high-density objects such as experiment packages are to be used in a water immersion simulation, addition of extremely low-density material such as foam may be required to make the object neutrally buoyant. However, use of closed-cell foam may introduce errors in the simulation due to its compressibility. A vertical displacement will result in a change in the ambient water pressure on the foam; hence, a change in the volume of the foam which results in a change in the magnitude of the buoyant force. The effect is such that the unbalanced force generated tends to increase the displacement, either upward or downward. The combination of large amounts of foam and variation of depth at which activity is performed can cause severe degradation of the simulation.

4.2 ROTATIONAL STABILITY

One of the most difficult problems experienced in application of the technique is rendering the subject neutrally stable in rotation. This condition exists when the buoyant force and the weight of the body continue to act through points that coincide as the body is rotated. Thus, a couple does not result with rotation of the body. An example of this condition was illustrated by the homogenous body of figure 3-7. Certain characteristics of the man-suit system make establishing the condition of neutral stability in rotation and maintaining this condition extremely difficult. These characteristics and some of the resulting problems are discussed below.

4.2.1 Center of Gravity and Buoyancy Changes

The most significant cause of the difficulty experienced in rendering the subject neutrally stable in rotation is the nonhomogenous characteristic of the body represented by the man-suit system. This characteristic results in the center of gravity of the system being offset from the center of buoyancy. Theoretically, the system can be balanced such that the center of gravity is made to coincide with the center of buoyancy, as illustrated in figure 4-1. In practice, this is difficult to do because of the problem of accurately predicting the location of the centers of gravity and buoyancy of the subject in advance. Unless these centers are located in advance, the method of trial and error has to be used during the balancing to render the subject neutrally stable in rotation. This method can be time consuming until some experience is gained with each particular man-suit system involved in the simulation. The centers are not made to coincide completely, but brought sufficiently close so as to make the resulting couple unnoticeable.

4.2.2 Movement Inside Pressure Suit

In most pressurized suits, the man is free to move around inside the suit. If the man-suit system were balanced such that the condition of neutral stability in rotation was obtained, this condition would be

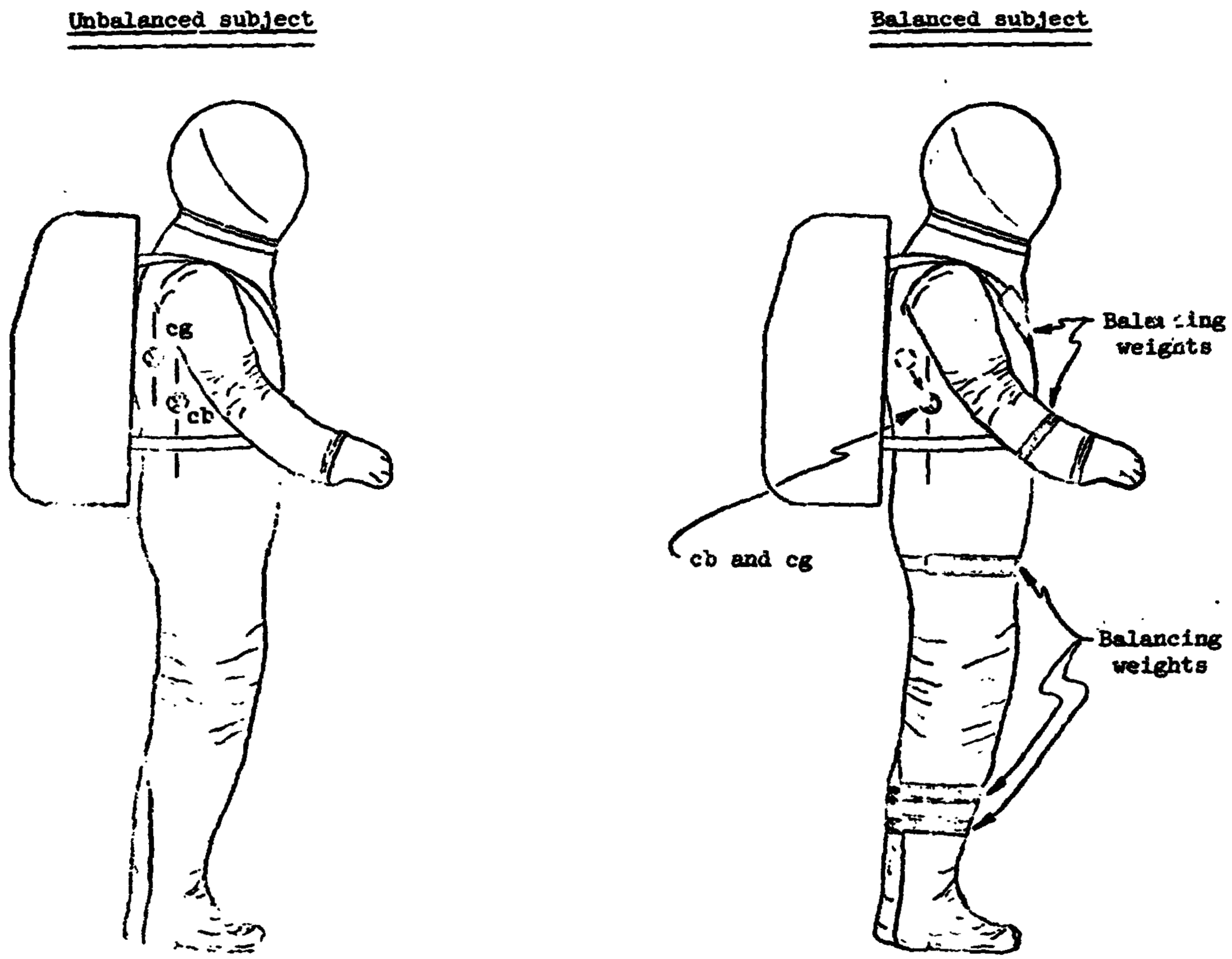


Figure 4-1.- Relocating subject's center of gravity to center of buoyancy.

upset when the subject moved around inside the suit, changing the location of the center of gravity of the man-suit system. Since the center of buoyancy of the system is not changed, the center of gravity is displaced from the center of buoyancy, and a couple results. This displacement of the center of gravity can be practically eliminated with a properly fitted suit. If a properly fitting suit is not available, padding strategically located inside the suit will minimize this displacement.

4.2.3 Man-Suit System Configuration Changes

The center of gravity of the man-suit system is also changed when the subject changes the configuration of the system by moving his arms and legs, et cetera. Since the density of the water is constant and the density of the man-suit system is not, the center of buoyancy is not displaced to the same point as the center of gravity. The resulting couple tends to rotate the subject about his center of gravity to a stable position or attitude as defined in section 3.0. Because of the limited mobility of the Gemini suits, the displacement of the center of gravity caused by the subject changing the configuration of the man-suit system was small. However, a definite preferred attitude can result, as was noted by the Gemini XII pilot during his evaluation of the fidelity of the technique. The total effect of the resulting couple upon the simulation has to be analyzed in context of the activity being simulated. If the subject is properly balanced for a particular man-suit configuration, a change from that configuration can result in a preferred attitude, which is not necessarily in either vertical or horizontal planes. The man-suit configuration required to perform activity in a horizontal plane can be such that the preferred attitude is in that horizontal plane. Hence, the subject may not detect that he has a preferred attitude, and the effect upon the simulation of this activity would be insignificant. The same man-suit configuration in the vertical planes may result in a detectable preferred attitude. Once a preferred attitude is detected, the subject can be rebalanced or the performance of the activity changed to a plane such that the subject does not experience a preference to a particular attitude. The performance of an activity may result in a continuously changing man-suit configuration, and the preference for a particular attitude will not be established or detected. Also, it is normally desired that the subject work from the neutral configuration of the pressurized suit in order to obtain the most efficient use of his energy, thereby minimizing the number of man-suit configurations and the effect of center-of-gravity changes on the simulation. Detection of a preferred attitude during performance of activity in which the subject is well restrained is difficult.

4.2.4 Displacement of Balance Weights

The inadvertent displacement of balance weights can cause a significant change in the location of the center of gravity of the man-suit system. This problem is the most easily solved through proper attention to the attachment of the balancing weights to the suit. However, observers should be made aware of the possibility of weight movement, and the need for prompt correction of the problem.

4.2.5 Relief of Trapped Air

The relief of air trapped in pockets of a multilayer suit was noted during simulations of Gemini EVA to cause difficulty in maintaining the subject in a condition of neutral stability. The relief of trapped air is related to the water absorption problem discussed in paragraph 4.1.1. The difficulty experienced with the relief of trapped air was noted to be more pronounced with suits which contained extra layers of insulation such as used on the Gemini extravehicular suits. Holes were punched into the outer layers of the suit to relieve this trapped air. The relief of trapped air or water absorption can effect a change in the center-of-gravity position, resulting in the suit having a preferred attitude; however, they were usually detected because of the displacement of the man-suit system resulting from the unbalanced force generated.

4.3 WATER DRAG

One of the most apparent limitations of the water immersion technique in simulating weightlessness is water drag. The total effect of water drag on the simulation is in part a function of the activity being simulated. It is most severe when the subject attempts to propel himself through the water. An example of this type of activity would be a task in which the subject attempted to push away from one vehicle and travel some distance to another. However, the result of the Gemini EVA experience indicates this type of activity is not desirable and should not be planned for an EVA mission. The Gemini XII pilot, who evaluated the fidelity of the simulation, observed that his initial motion history during the simulation was very similar to his in-flight experience. He commented that after the initial phases of the motion, the effect of damping of the water on the remaining motion history made it noticeably different from his in-flight experience.

During activity in which the subject is restrained, the effect of water drag is practically eliminated. During movement, if the subject performs slow, deliberate movements of his limbs and does not attempt to rapidly accelerate his body, the water drag will be minimized. While this method of operation may appear to compromise the simulation, it does not, because pressurized suits naturally restrict the subject's mobility, and a slow, deliberate method of operating results. Slow and deliberate performance of most activity is desired because it results in the most efficient use of the subject's energy in operating against the suit. This type of operation was also found desirable during Gemini EVA in order to minimize the buildup of momentum; and hence, the forces required for body control.

4.4 MAN-SUIT DYNAMICS

Some aspects of the man-suit dynamics experienced underwater are not representative of what would be experienced during the same activity performed in space. The causes of this variation in the man-suit dynamics are inherent in the water immersion technique and are discussed below along with the resulting effect upon the simulation.

4.4.1 Man-Suit Contact

As has been stated previously, the subject is somewhat free to move around inside of the pressurized suit. This means that the immersed subject floating freely with his body vertical would be standing on the boot bottoms or sitting on the crotch of his suit. If the subject was floating with his body horizontal, he would sense that he was lying against the suit. Hence, the subject is aware of gravity, and has an unrealistic gravity reference system as compared to actual flight conditions. The Gemini XII pilot noted this man-suit contact as one of the most significant differences between the underwater experience and his in-flight experience.

The effect of this problem can be minimized by providing the subject with a properly fitted suit. If this is not possible, strategically located padding will minimize the effect. The subject can approach his task from different orientations in order to be confronted by a variety of man-suit contact references. This would minimize the possibility of the subject's performance of a task being biased by a reference to a particular position inside the suit.

4.4.2 Sensed Mass

Another cause of the difference in the man-suit dynamics experienced underwater as compared to that experienced in space is the addition of balancing weights to the man-suit system. The balancing weights render the subject weightless underwater, but also increase the mass (and inertia) of the man-suit system. Generally, a larger percentage of the mass that is added goes into the torso area, whereas a much smaller percentage goes into the limbs. Hence, the effect of this increased mass is less pronounced when the subject moves only an arm or leg of the suit as compared with moving his whole body, as would be the case when the subject is restrained. If the subject desired to accelerate his body, he would have to generate a greater force to accomplish this underwater due to his larger mass.

The subject generally does not sense this increase in mass for several reasons. Operating in a pressurized suit and working against the suit forces renders the subject insensible to the balancing weights attached to the suit. Also, since the subject does not have an immediate reference for the forces required for movement in space, he is not aware of generating greater forces underwater.

The larger mass in the man-suit system can result in a greater work output by the subject in performing activity underwater as compared to performing the activity in space. However, any adverse effect on the simulation by the mass of the man-suit system not being simulated is minimized as the work expended in body restraint and positioning is reduced. The reduction of work so expended is one of the primary objectives of equipment design and crew training.

5.0 APPLICATIONS OF THE TECHNIQUE

The water immersion technique has provided a method for simulating the in-flight activity with no time-line discontinuities. Thus, a means is afforded for evaluating and developing man's capability in a weightless environment. The technique can be applied to the resolution or prediction of many problems associated with operating in a weightless environment. This section of the report will discuss the application of the technique to the evaluation and development of EVA flight plans. The value of the technique in training crews for performing these EVA flight plans is also discussed.

5.1 EVA FLIGHT PLANS

Experience with EVA during the Gemini Program indicated successful completion of the EVA could be considerably enhanced by giving careful attention to EVA flight planning. If proper attention was given such items as body restraint and positioning problems, workload control, and rest periods, EVA could be successfully performed as planned, as demonstrated on Gemini XII. The Gemini XII EVA flight plan was unique in that it was the first to be evaluated, developed, and demonstrated by the flight crews using the water immersion technique. The EVA flight plan was composed of a large number of tasks. The performance of each task was described by detailed procedures commensurate with the difficulty of the task. By simulating weightlessness for long periods with a high degree of fidelity, the water immersion technique provided an experience of the EVA flight plan on an end-to-end basis. This preview enabled evaluation and development of the EVA flight plan.

5.1.1 Task Evaluation

The water immersion technique can provide the necessary information for determining the feasibility of a particular task. Performance of a task underwater is very indicative of the relative difficulty and workload requirements of the in-flight experience because of the near duplication of the weightless environment. The task continuity provided by the technique assures realistic initial conditions for each task and enables a realistic determination of the time required to perform each task; and thus, whether a task is compatible with the total flight plan. The capability to perform a difficult task may also be developed once the constraining factors such as lack of adequate body restraints or handholds are identified by underwater simulation. The sequencing of detailed procedures for performing each task and the sequencing of various sks can be evaluated and developed because of the capability to perform them on an end-to-end basis. Hence, the most efficient use of the crewman's energy and time can be determined.

5.1.2 Definition of Body Restraint and Positioning Problems

The water immersion technique has particular applicability for identifying body restraint and positioning problems because it duplicates the extravehicular crewman's in-flight condition for long periods. EVA experienced during the Gemini Program has emphasized the importance of task continuity for adequately determining these problems. The continuous simulation of weightlessness allows for determining the restraint requirement for each procedural step in the performance of a task. Body restraint may be required for only a few of the many detailed procedures required to perform a task. Uninterrupted performance of a task affords the opportunity to optimize the restraint for simplicity and determine criteria for selecting the best restraints for a task.

In the performance of most EVA tasks, body position with respect to the work area or certain spacecraft features is extremely important. These positions and the procedures and equipment required to attain them are readily identified in the long-term simulation afforded by the water immersion technique. This use of the technique was demonstrated on Gemini XII, and the procedures and equipment requirements for body positioning and translation were very accurately predicted.

5.1.3 Hardware Operational Requirements and Environmental Compatibility Evaluation

Since the water immersion technique can duplicate the extravehicular crewman's in-flight condition, the compatibility of hardware operational requirements with the weightless environment can be determined. Gemini experience has provided some criteria for design of equipment for operation by the crewman in a weightless environment. However, generalization from design criteria determined from operation of specific hardware to the design of all hardware can result in operational requirements that remain incompatible with the weightless environment. The water immersion technique affords a means of determining whether a crewman can operate specific hardware in a weightless environment. Requirements for modifications to hardware to render it compatible with the environment can be determined. The continuous simulation of weightlessness means the history of interplay between the subject and individual hardware items can be evaluated. Questions such as whether a crewman can operate a particular hardware item while maintaining possession of other hardware and his body positioned can be answered.

5.1.4 Time-Line Evaluation and Development

Realistic prediction of the time required to complete a task as well as the total time for performing an EVA flight plan is a necessary requirement for having an EVA capability. Experience with the water immersion technique indicates it is especially applicable to predicting times required to perform a variety of tasks. The Gemini XII EVA flight plan consisted of a variety of tasks which were performed along a time-line predicted from evaluation of the EVA flight plan using the water immersion technique. The performance of the EVA in flight never varied more than a few minutes from its performance underwater.

Proper placement of rest periods during the EVA is also very important to the successful completion of the EVA. Because of the capability to perform the EVA on an end-to-end basis, the water immersion technique provides a realistic buildup of the workload for performing the EVA. The crewman's condition or workload profile has direct reference to the EVA time-line and provides the necessary criteria for spacing the rest periods. This information was used to determine the rest period requirements in the Gemini XII EVA flight plan.

5.2 CREW TRAINING

Flight crew performance of the EVA flight plan in the weightless environment provided by the water immersion technique has certain advantages for crew training. Based on several preflight training runs and one postflight verification run, the Gemini XII pilot concluded that the water immersion technique duplicated his in-flight experience with a high degree of fidelity. The Gemini IX-A pilot made similar comments after a postflight simulation of his EVA, using the water immersion technique. Hence, if proper attention is given to duplicating the total EVA experience, including reasonable fidelity hardware and spacecraft, the EVA experienced underwater will be an accurate review of the in-flight experience.

5.3 FLIGHT PLAN CONFRONTATION

Detailed procedures such as those in EVA flight plans provide adequate information for relating what has to be done to complete a task. However, there is much valuable operational information which cannot be adequately stated in the procedural steps, but which can considerably enhance performance of a task. This information can be only acquired by a personal performance of the task. Task continuity is required if a valid subjective experience of the task is to be realized. The water immersion technique, by providing a continuous simulation of weightlessness, enables a personal experience of not only the total task, but the complete EVA flight plan. In addition, crew performance of EVA flight plans in the weightless environment provided by the water immersion technique provides a basic introduction to operating in the continuous weightless environment of space.

6.0 FIDELITY CONSIDERATIONS IN APPLICATION OF TECHNIQUE

Previously it was stated that if proper attention was given to duplicating the total EVA experience, the EVA experienced underwater could be considered a prerun of the in-flight experience. In duplicating the total EVA experience during the Gemini Program, a variety of miscellaneous EVA equipment and vehicle mockups were used underwater. The EVA equipment used included such variety as fabric tethers of several inches to over a hundred feet in length and the Astronaut Maneuvering Unit backpack. Vehicle mockups of the Gemini spacecraft, Gemini spacecraft adapter section, and the Agena/target docking adapter (TDA) were also used. Each EVA equipment item or vehicle mockup not represented in the simulation of the EVA experience compromises the simulation. This section of the report will discuss some of the fidelity considerations that should be given to miscellaneous EVA equipment and vehicle mockups to provide a valid simulation of the total EVA experience. The effect of suit fit on the fidelity of the simulation is also discussed.

6.1 BUOYANCY

The fidelity of the simulation is enhanced if all EVA equipment is neutrally buoyant or has the appearance of being weightless. EVA equipment items which tend to float up or down when released by the crewman, or while tethered, compromise the simulation. The simulation cannot duplicate the actual motion of EVA equipment items in flight because the motion is the result of many factors; however, the simulation should not provide for motion that cannot be expected in flight. As an example, a camera which is not neutrally buoyant will tend to remain at the end of its tether, and does not provide a realistic preview of the possible motion of the camera in flight. If such unrealistic motion of EVA equipment is prevented during the simulation by rendering the equipment weightless, activity such as the interplay of the crewman, EVA equipment, and the space vehicle can be reviewed with confidence for prediction and solution to operational problems, such as tethers becoming entangled, or the equipment catching on some extension of the space vehicle as thrusters, or antennas. Larger equipment items such as the backpack maneuvering unit used during the Gemini Program will seriously compromise or interrupt the simulation if they are not neutrally buoyant. Such equipment, depending upon its buoyant force, could carry the crewman immediately to the water surface or pool floor once made a part of the man-suit system. During the Gemini simulations, the chestpack was part of the man-suit configuration and was rendered weightless with the man-suit system during the initial balancing. Equipment which becomes part of the man-suit system during the EVA, such as the Gemini backpack maneuvering unit, should be rendered weightless prior to the simulation. If such equipment is not rendered weightless prior to the simulation, the simulation would have to be interrupted to render the man-suit-donned equipment weightless, or weightless equipment substituted. The buoyant force of either simulated umbilicals supplying the crewman with oxygen (air) and communications, such as the 25-, 30-, and 50-foot umbilicals used with the chestpack, or umbilicals required for life support during the simulation can adversely affect the weightless condition of the man-suit system. During the Gemini simulations, the effect of the umbilical buoyant force was minimized by adding weights to the umbilical. Some equipment can be used without consideration of its weight without compromising the simulation. Most fabric tethers have a density such that they appear weightless when immersed into water. Equipment that is fixed or restrained during the activity can be used without rendering it weightless. The Gemini backpack maneuvering unit was restrained to the vehicle duirng the checkout and donning procedure. Scientific experiment packages such as the micrometeorite collecting package were fixed to the vehicle.

EVA equipment is generally not required to be neutrally stable in rotation; however, in some activity simulated the lack of neutral stability in rotation may compromise the simulation. Such would be the case if the crewman had to transport, manipulate, or control an equipment item in which the mass of the item approached or was greater than the mass of the crewman. As an example, when a massive backpack which is not neutrally stable in rotation is donned, it would tend to rotate the crewman to its stable or preferred attitude.

Simulation of the weightlessness of space vehicles was not a consideration during the simulation of Gemini EVA. In simulation of activity in which the mass of the vehicle involved is relatively large compared to the crewman, such as the Gemini spacecraft, the vehicle can be assumed as a fixed reference for the EVA. A vehicle mockup restrained to a fixed position underwater provides a reference for the extravehicular crewman, just as the flight vehicle does during the in-flight experience. However, the dynamics to be simulated involve three bodies (spacecraft, crewman, and EVA equipment), as was demonstrated by the perturbations to the spacecraft's motion caused by the Gemini IX-A pilot's activity in the spacecraft adapter section. Since the three-body problem was the result of unplanned excessive and inefficient use of the pilot's energy during the activity, the activity simulated can generally be assumed to involve a two-body problem (crewman and EVA equipment), with the vehicle serving as a reference for the EVA.

6.2 MASS

Mockups of flight equipment can be constructed to simulate weightlessness or to represent actual equipment mass; however, simulating weightlessness as well as mass is difficult because of the constraints of having a mockup flight configured (fixed volume) and neutrally buoyant (fixed density).

As a general rule, if the crewman does not have to deal with massive equipment personally, the simulation of weightlessness is more significant than having equipment mass duplicated. An analysis of specific tasks should be made to determine to what extent the simulation would be compromised if equipment mass is not simulated. If the analysis reveals the simulation of mass to be significant, then simulation of the activity by means of some other technique will be necessary, unless the simulation of mass and weightlessness can be accomplished simultaneously. Exceptions to this would be related to simulations in which the requirement for the equipment to be weightless or flight configured is relaxed. An example of this kind of activity would be the restrained crewman jettisoning equipment.

As was discussed in section 6.1, space vehicles can be assumed to provide a fixed reference for the EVA because their relatively large mass (inertia) results in little or no motion being produced by the crewman during performance of the EVA. Hence, simulation of the mass of the space vehicle is not a requirement since its motion during EVA is not significant. Simulation of the mass of moving parts of space vehicles, such as hatches or couches, would contribute significantly to the fidelity of activity in which the crewman had to handle such parts.

6.3 MATERIAL AND CONSTRUCTION

When functional training hardware cannot be used in the underwater simulation because it is not neutrally buoyant or possible damage to functioning systems and their components may result, buoyant mockups of the hardware can be constructed. The mockup should be designed such that weights or foam can be added, if necessary, to render the mockup neutrally buoyant. The amount of weight or foam required can be minimized by choosing materials having a density which approximates that of water for construction of the mockup. To avoid compromising the simulation, the mockup should be configured as the flight item. Generally, this means the mockup has external characteristics similar to the flight item. The mockup should have external controls such as switches, valves, and levers that are operative but not functional. The construction of the mockup should be such that it affords no greater or lesser advantage in gripping or handling than the flight article during the in-flight experience.

Mockups of space vehicles should be configured as the flight vehicle. The exceptions to this would result from the fact that the crewman did not interface with the complete vehicle. During activity in which the area of operation of the crewman can be accurately predicted in advance, only the configuration of the flight vehicle in that area would be required for the mockup.

The crewman operating in the weightless environment of space is almost continuously confronted with body restraint and positioning problems until he has fixed his position by use of a restraint system. After fixing his position with a restraint system, the crewman must move and position his body to perform useful work. As a result of his situation in a weightless environment, the crewman's capability for force generation is a significant factor in determining his mobility. A general rule for material and construction considerations of vehicle mockups is that the crewman should have no greater or lesser capability for force generation than he would have with the flight vehicle in the weightless environment of space. Specifically, corners, curved surfaces, cavities, and extensions such as antennas and thrusters with which the crewman may come in contact should be represented. These items may provide mobility aids during the EVA, or cause interference with the crewman's performance of the EVA. The material used for contact surfaces should be such that the crewman has no additional hand- or foothold provided, as would be the case if expanded or corrugated metal were used. If the materials selected do not resist corrosion, some protective coating should be used, since degradation of the mockups will occur with prolonged periods of immersion.

The internal geometry of the vehicle, as well as volume, should be accurately represented by the mockup in order not to increase or decrease the crewman's capability for force generation. Couches, hardware stowage containers, and other equipment which defines the internal geometry should be included. The Gemini intravehicular activity (IVA) was not representative of what the IVA experience in the Apollo spacecraft will be; however, a generalization of the Gemini IVA and EVA experience indicates that an accurate representation of the crewman's operating volume and geometry is important for successful simulation of IVA, including preparation for EVA. Consideration of crew safety dictates that the crewman be knowledgeable of hazardous or undesirable operating areas in the vehicle. An accurately represented internal volume is also important to developing the necessary coordination between crewmembers and equipment.

Spacecraft viewports, hatches, and restraint systems are examples of other items which should be provided in the mockup of the flight vehicle to simulate the total in-flight experience. The inclusion of spacecraft viewports incorporates into the simulation the realistic EVA visibility constraints for the crewman in the vehicle. During some missions it may be desired to restrict the EVA to this area. Operation of spacecraft hatches was a significant task during Gemini EVA. Hatches should be configured as the flight item, especially functional operating mechanisms. The crewman cannot experience the hatch opening and closing task unless the hatch used in the vehicle mockup is a functioning representative of the flight item. Simulation of hatch mass may be required to have valid experience of the task. Restraint provisions on the spacecraft should also be configured as the flight item in most of their detail. A thorough evaluation of the restraint system is possible because of the continuous simulation of weightlessness by the water immersion technique.

6.4 SUIT FIT

One of the main advantages of the water immersion technique is the capability to simulate weightlessness for long periods. Because of these long periods of weightlessness, tasks can be performed without time-line discontinuities, which is necessary for determining task feasibility and training flight crews. A valid determination of task feasibility requires a good suit fit. The effort required to perform the task and the associated metabolic workload cannot be representative of the in-flight conditions unless the extravehicular crewman's in-flight body mobility is duplicated during the simulation. Since suit fit for actual space flight is always as good as possible, a good suit fit is especially important in the training of flight crews, where the emphasis must be on accurate simulation of the in-flight conditions. The restricted mobility of the pressure-suited subject gives validity to the simulation, since it duplicates the condition of the extravehicular crewman. However, a good suit fit is required to accurately duplicate the condition of the extravehicular crewman because the restriction to mobility imposed by the pressurized suit is highly dependent upon the quality of suit fit.

7.0 SUMMARY

In summary, if careful attention is given to providing and maintaining the crewman in a condition of neutral stability in translation and rotation, and to the fidelity considerations of EVA equipment and vehicles involved in the EVA, performance of the EVA underwater can be considered a prerun of the in-flight experience. A definition of workload, restraint, rest period, and time requirements, as well as task difficulty is provided by the water immersion technique, which can considerably enhance EVA flight planning. The water immersion technique makes possible a demonstration of the EVA flight plan on an end-to-end basis. This demonstration by the flight crews can increase the probability of successful performance of the EVA.

8.0 REFERENCES

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